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SATELLITE SURVEILLANCE AVOIDANCE OPTIMIZATION AID

DECISIONS AND DESIGNS INCORPORATED

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SATELLITE SURVEILLANCE AVOIDANCE OPTIMIZATION AID

by

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SUMMARY

Recent technological advances have made possible sophisticated data-gathering capabilities for earth-orbiting spacecraft. Naval forces would appear to be particularly vulnerable to satellite surveillance since they operate on the surface of uniform, low-noise oceans where camouflaging is difficult. Thus the problem facing the commander of a task force is how to move his force when secrecy is important.

A methodology is presented for helping a naval commander avoid satellite surveillance. With known satellite orbital characteristics, the time and location of detection zones along a ship's planned route can be calculated. The methodology suggests how a commander can avoid many of these detection zones by varying his speed of advance (SOA) during his transit.

A computer decision aid based on this methodology has been developed. It considers probabilistic information, such as the probability that the weather will permit detection by a given satellite and the probability that a particular evasive action will thwart detection, along with user provided cost functions for factors such as aversion to detection and costs of evasive actions to calculate expected cost for the detection zones encountered using a given SOA profile. A dynamic programming algorithm is then used to determine the SOA profile which minimizes expected cost for a given transit.

CONTENTS

CONTENTS (cont.)

FIGURES

ACKNOWLEDGMENT

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SATELLITE SURVEILLANCE AVOIDANCE OPTIMIZATION AID

1.0 INTRODUCTION

Adversary surveillance has long been a concern of naval commanders at sea. Not only can it identify a naval task force as a possible military target, but it may also lead to an unwanted confrontation with possibly far greater military and political consequences.

Ships at sea are potentially subject to many kinds of surveillance. Traditionally, the important components of a surveillance system have been aircraft, shipping, submarines, land-based radar, and communications sensors. Future surveillance systems can be expected to include land-based acoustic sensors and earth-orbiting satellites with varied sensing capabilities.

It is possible to avoid some of these surveillance systems by careful pre-transit *planning.* In many cases, the task force commander may plan to avoid areas of the ocean in which he is likely to be detected by land-based sensors, merchant traffic, aircraft, or submarines. In addition, he may plan to follow a deceptive route so that, if he is detected, his intentions and destination will be difficult to infer. The result of this planning would be a track plan, which consists of a specified transit route. A hypothetical track plan from Norfolk, Virginia to the Straits of Gibraltar is illustrated in Figure 1-1.

The presence of satellites with surveillance capabilities would greatly diminish the effectiveness of a track plan, which is intended to circumnavigate areas of the ocean where surveillance is likely. Since surveillance satellites can cover all areas of the ocean, a track plan by itself would

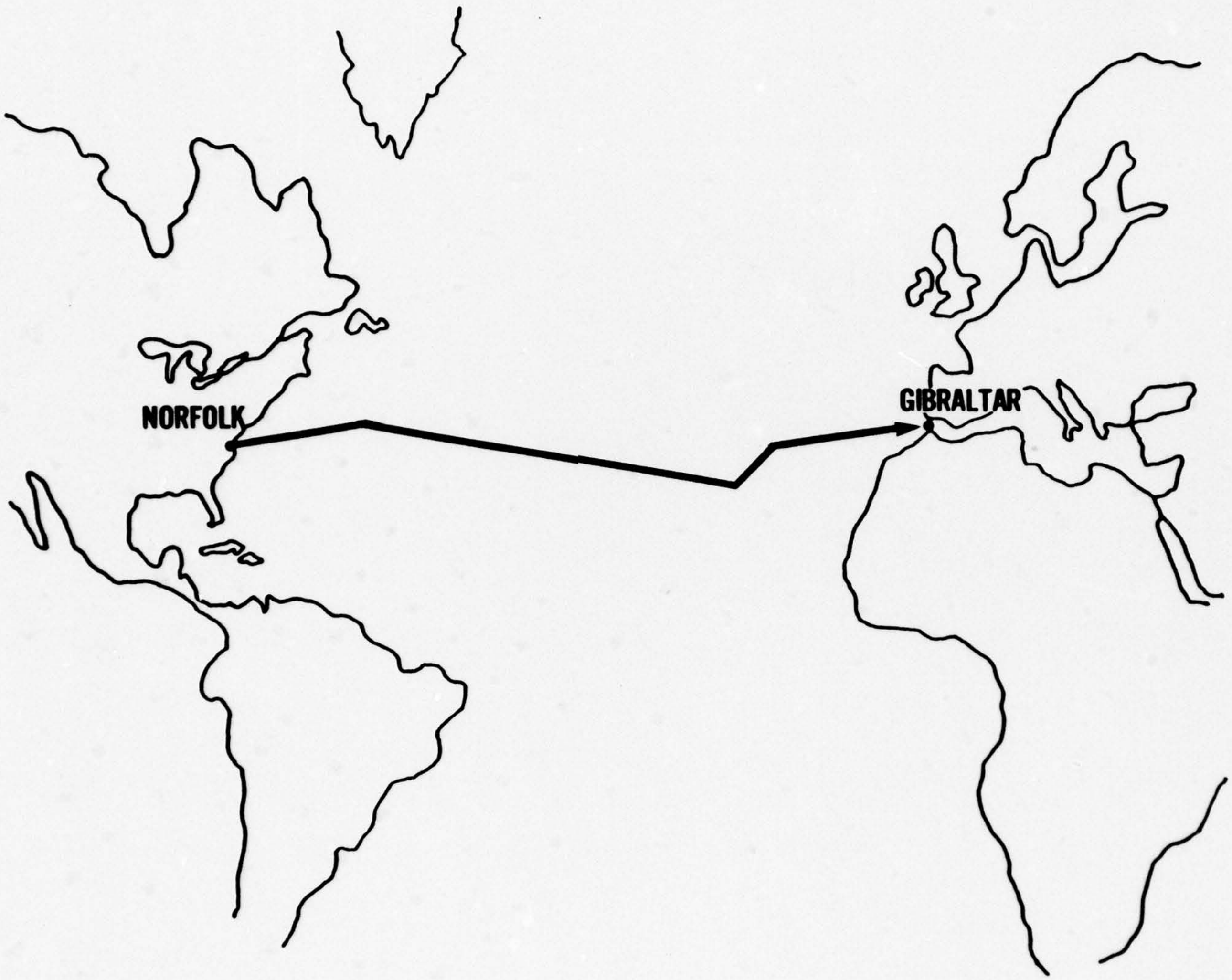

Figure 1-1

A HYPOTHETICAL TRACK PLAN FROM NORFOLK TO GIBRALTAR

be an ineffective countermeasure for satellite surveillance.

The task force commander can, however, predict a satellite's motion and use that information to his advantage. The ephemeris data for an adversary satellite is either known or can be calculated from observation data. The ground track, which is traced out by movement of the satellite's sub-orbital point across the earth's surface, can then be predicted with precision. The satellite's ground track will usually intersect the commander's track plan at regular, predictable intervals.

One pass of a satellite over the track plan is represented by the ground track segment A in Figure 1-2. The dotted lines on either side of A represent the satellite's effective field of vision. If, at the time of this pass, the task force is in the segment of its track plan within this field of vision, then *detection is possible.*

As the satellite follows its orbital trajectory, the earth precesses from west to east underneath it. Thus, after one orbital revolution, the same satellite may again cross the track plan with ground track B, which is to the west of A.

A typical non-synchronous satellite with surveillance capabilities normally has an orbital period of about ninety minutes. The time interval between successive detection zones, like those associated with A and B, is roughly equal to one orbital period, depending on the angle of inclination between the ships' track plan and the satellite's ground track. Furthermore, from the vantage point of the task force commander, each detection zone lasts for only a few minutes because the satellite moves so quickly; for a

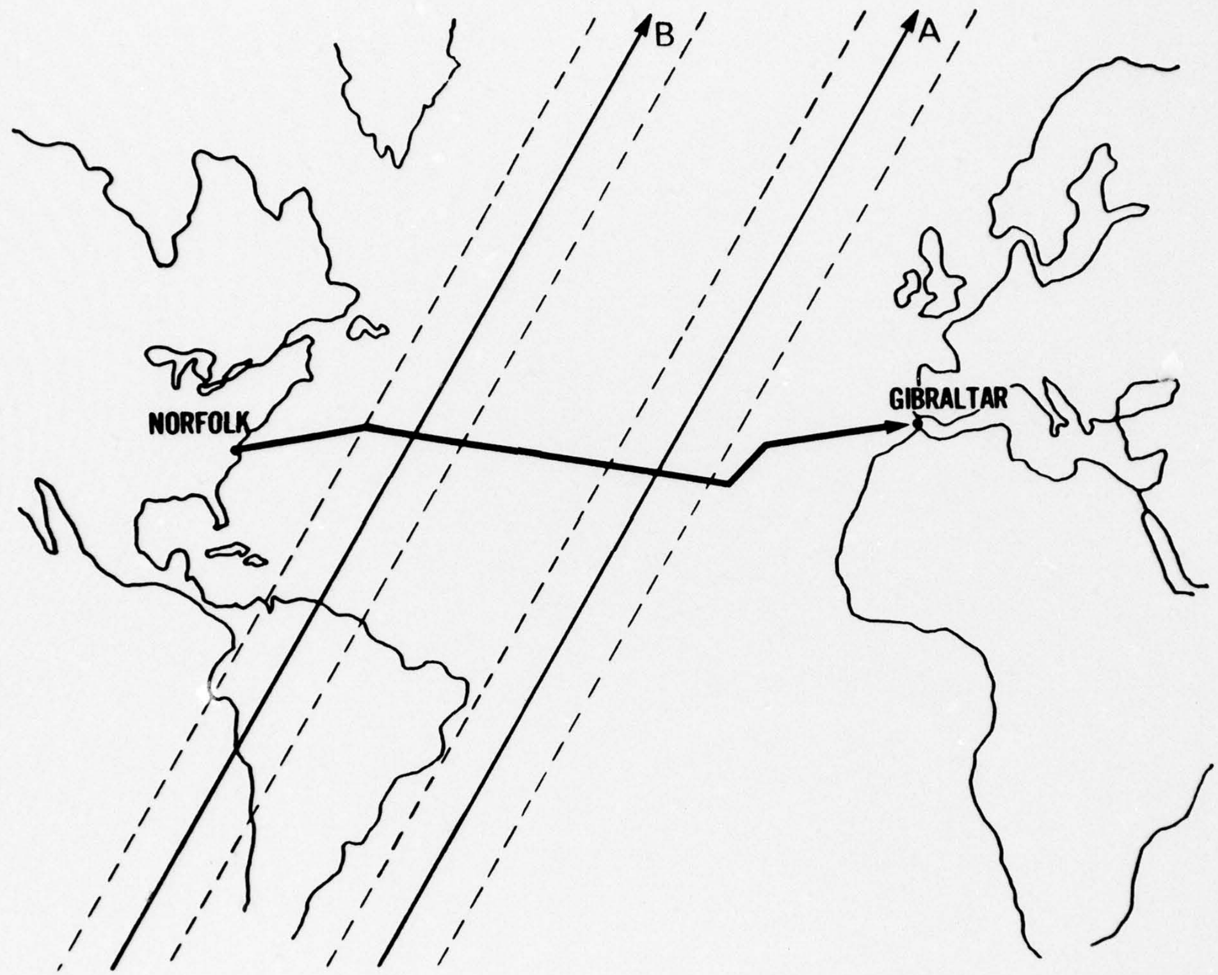

Figure 1-2

TWO SATELLITE PASSES OVER A HYPOTHETICAL TRACK PLAN

satellite having a ninety-minute orbital period and an effective swath diameter of 1,000 nautical miles, the ships' exposure time to surveillance would be less than four minutes.

Thus, each detection zone in Figure 1-2 occurs at a particular time and lasts for only a few minutes. Even if the commander must depart from his origin and arrive at his destination at specified times, he may be able to avoid surveillance from satellite passes A and B entirely by changing his speed of advance (SOA) at appropriate points enroute.

If the transit requires several days, however, a given satellite would normally pass over the track plan many times, and selecting the appropriate SOA to use at various times may become rather complex. The problem is further complicated when there are many surveillance satellites, each with different orbital characteristics and sensing capabilities.

The methodology discussed in this report was developed to help the naval commander understand during transit planning exactly what satellite surveillance he faces and what he can do to avoid it. This methodology has been incorporated into a computer implementation called the Satellite Surveillance Avoidance Optimization Aid. This Aid is planned to be installed in the Advanced Command and Control Architectural Testbed (ACCAT) at the Naval Ocean Systems Center (NOSC) in San Diego in order to test the efficacy of the concepts which it embodies and to determine desirable enhancements.

2.0 GENERAL METHODOLOGY

The basic approach developed by DDI to aid the naval commander in avoiding surveillance by satellites is outlined in this section. The essence of the approach is to determine for a planned transit route a series of speeds of advance which avoid placing the task force in regions of the route within the view of satellites overhead at any instant in time.

First, the approach is described in an intuitive manner using a graphical representation of the problem. Next, the limitations of this simplistic solution are discussed. Finally, a generalized version of the approach is described.

2.1 A Graphical Representation

The satellite surveillance zones along a track plan and some possible ways to avoid them can be represented graphically. For illustration, assume that a commander is required to leave Norfolk at 4 P.M. on November 27 (Greenwich mean time) and is expected to arrive at Gibraltar nine days later, at 4 P.M. on December 6.

He first selects a track plan, which may be along a great circle or along a more complicated route consisting of great circle segments. Helping the commander select a track plan is beyond the scope of this methodology since that decision depends on many transit-specific factors such as the location of land masses, shipping lanes, and land-based adversary surveillance.

Suppose that a track plan like that in Figure 1-1

has been selected and that the length of the transit according to this plan is 3,240 nautical miles. Figure 2-1 represents the distance along the track plan on the vertical axis. Time after departure is represented on the horizontal axis.

Each vertical line segment in Figure 2-1 represents a satellite passing over a portion of the track plan. Assume, for example, that pass A in Figure 1-2 occurs sixteen hours after the departure from Norfolk. That pass is then represented by line segment A in Figure 2-1. The length and vertical position of this line segment specify the portion of the track plan that is within the satellite's effective field of vision. The horizontal position of the segment shows the time when this pass occurs (16 hours after departure), and its width is the exposure time. As indicated above, since the exposure time would be just a few minutes for a non-synchronous satellite, the line segment is very thin when plotted on a time scale measured in days.

After one orbital period, the satellite again passes over the track plan and generates another line segment, B. In a similar fashion, each pass of the satellite over the track plan during the nine-day period can be represented.[1] Note that these line segments can be calculated and plotted by computer for any given departure and arrival times, track plan, and satellite ephemeris data.

The ships' position along the track plan at any point in time can also be represented on this graph. As the task

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[1]Figure 2-1 was generated for a satellite with optical sensors only. Since these sensors cannot "see" at night, nighttime passes were not plotted. A similar graph for an infrared satellite, which is not affected by darkness, would show about twice as many detection zones.

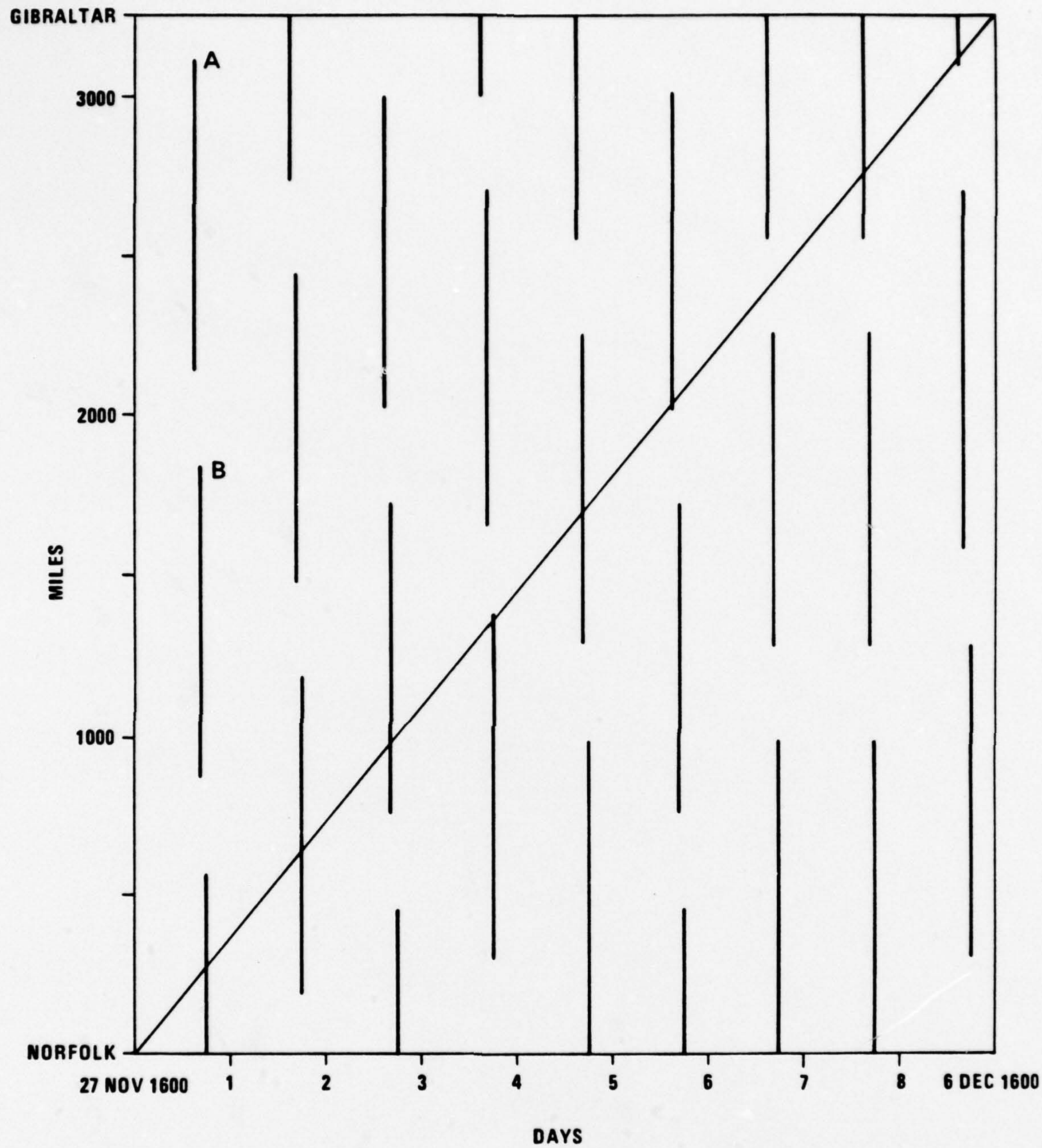


Figure 2-1
A GRAPHICAL REPRESENTATION OF SATELLITE DETECTION ZONES

force moves from Norfolk to Gibraltar, it traces out a path from the lower-left to the upper-right corner of the graph. A task force that moves with a steady 15-knot speed, for example, makes the 3,240-mile transit in exactly nine days and traces out the diagonal path shown. This path passes through eight detection zones. The commander can avoid some of these detection zones by varying his speed enroute. For example, if he follows the SOA profile V in Figure 2-2, he will encounter only three detection zones.

Avoidance of detection zones would be a rather simple matter if ships could move at any desired speed. Realistically, however, there are constraints within which the commander must operate. For example, he may wish to arrive on schedule and to use speeds that are between 5 and 25 knots. These requirements limit his possible speed profiles to those within the parallelogram in Figure 2-2. If the task force travels at the minimum speed of 5 knots for the first four and a half days, it will trace out boundary a. Then, in order to arrive on time, it would have to use maximum speed for the rest of the way, following boundary b. Boundaries c and d may be similarly interpreted. If all detection zones are assumed to have equal importance, the speed profile V is an optimal solution within these constraints.

If there are several surveillance satellites, however, the task of avoiding detection zones becomes more complex. The detection zones for five hypothetical surveillance satellites are plotted in Figure 2-3. By using a steady 15-knot speed in this case, the commander would face forty-two detection zones during his nine-day transit. It may still be possible to plot a series of speeds of advance on the graph that avoids many of these detection zones, although it becomes extremely difficult for large numbers of satellites.

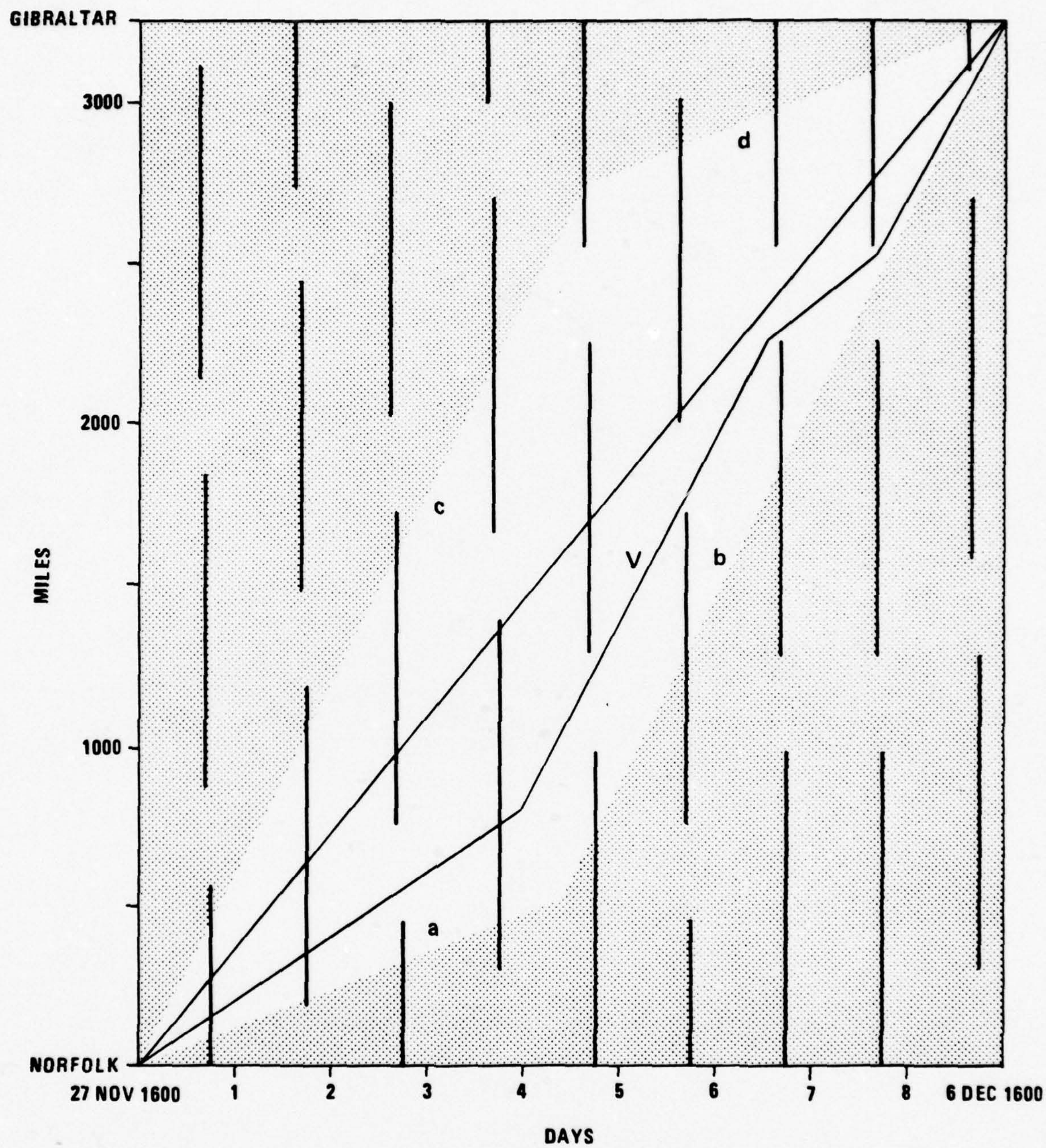


Figure 2-2

AN OPTIMAL SPEED PROFILE WITHIN VELOCITY CONSTRAINTS

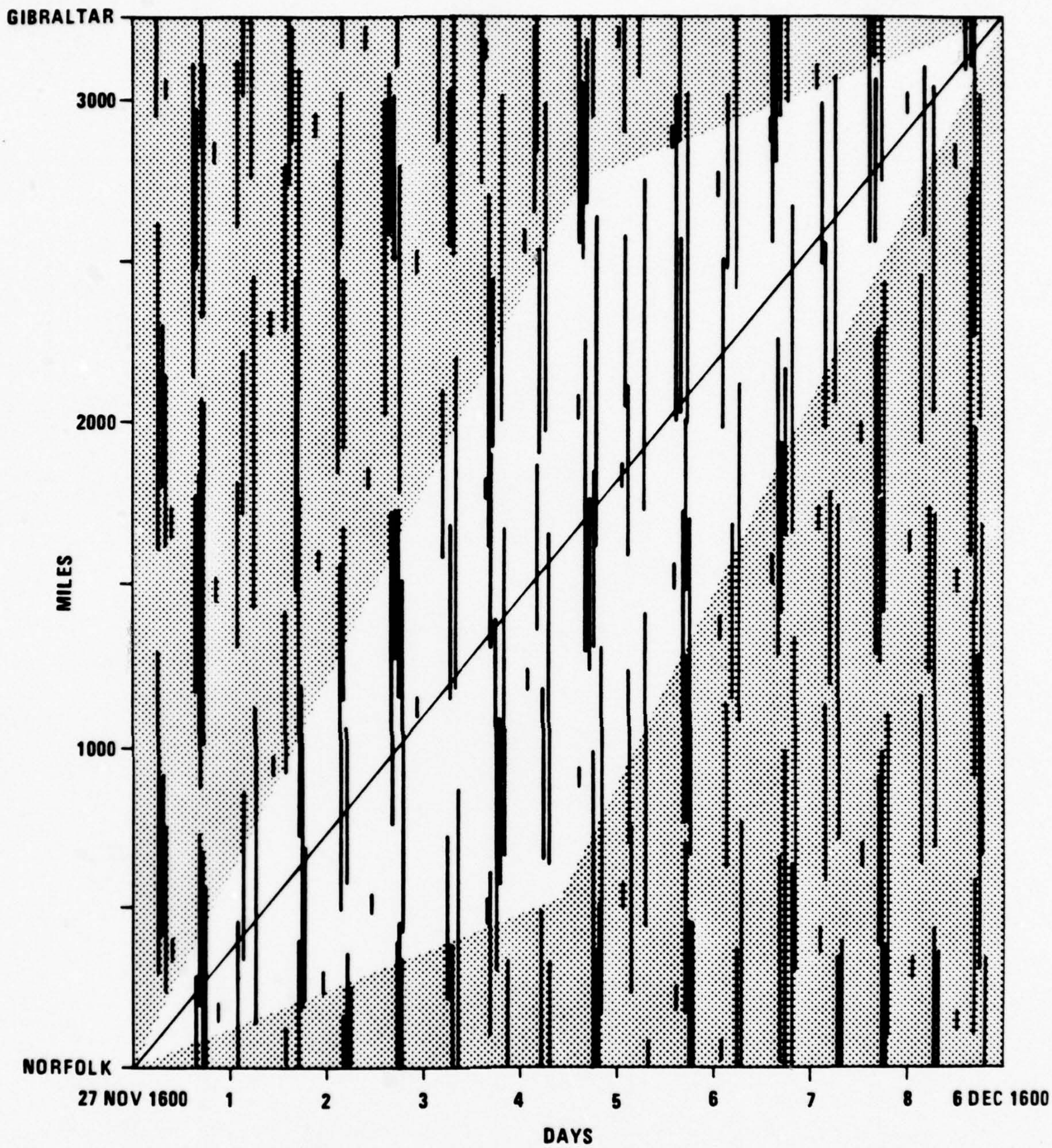


Figure 2-3
DETECTION ZONES FOR FIVE SURVEILLANCE SATELLITES

2.2 Limitations Of The Graphical Approach

If all detection zones are equally important to avoid, then the solution approach suggested above is a good one: trace a path through the maze of detection zones which misses as many as possible without exceeding the maximum speed of advance, or falling below the minimum speed of advance.

Passing through a detection zone, however, does not necessarily mean that the task force will be detected. If cloudy weather is forecast for the first few days of the transit, for example, the probability of detection by an optical satellite during that period will probably be very small. At the same time, the sensing capabilities of a radar satellite generally are not affected by cloud cover. Accordingly, it may be preferable to pass through two or more optical detection zones rather than a single radar detection zone. Therefore, the probability of detection within a detection zone, which is not represented in Figure 2-3, may be an important consideration in choosing a speed profile.

The cost of a detection may also be important. Are early detections more costly than later ones? Is the first detection more costly than subsequent detections? In addition, all speeds of advance are not equally costly. It may be preferable to risk a detection which has a low probability rather than maintain the maximum speed of advance for an extended period of time.

If models for the probability of a detection, the cost of a detection within each detection zone, and costs of speeds of advance are available, then we can select the SOA

profile that minimizes the expected cost of the transit.

Finally, it may be possible to lower the probability of being detected by a given satellite through the use of various evasive actions such as EMCON, electronic countermeasures, etc. Both the efficacy and costs of these measures should be included.

2.3 Generalized Approach

Using the methodology discussed above, a computer-based decision Aid for helping the naval commander to avoid satellite surveillance has been developed. An overview of the Aid is shown in Figure 2-4.

The Aid is designed so that only a small number of parameters is required as user inputs. Important probabilistic information and current satellite ephemeris data are assumed to be supplied through a land-based computer network. Based on inputs from the network and the user, the optimization procedure provides the commander with a recommended SOA profile and all relevant satellite surveillance information. Since development and integration of the components of such a system are no small tasks, an operational version of the Aid is still years away.

2.3.1 Optimization Procedure - A dynamic program searching over discrete SOA options is used to find a recommended SOA profile through a pattern of detection zones. In consideration of the limitations discussed in Section 2.2, a probability model is used to compute the probability of detection within each detection zone, and cost profiles for detection, evasive actions, and speed

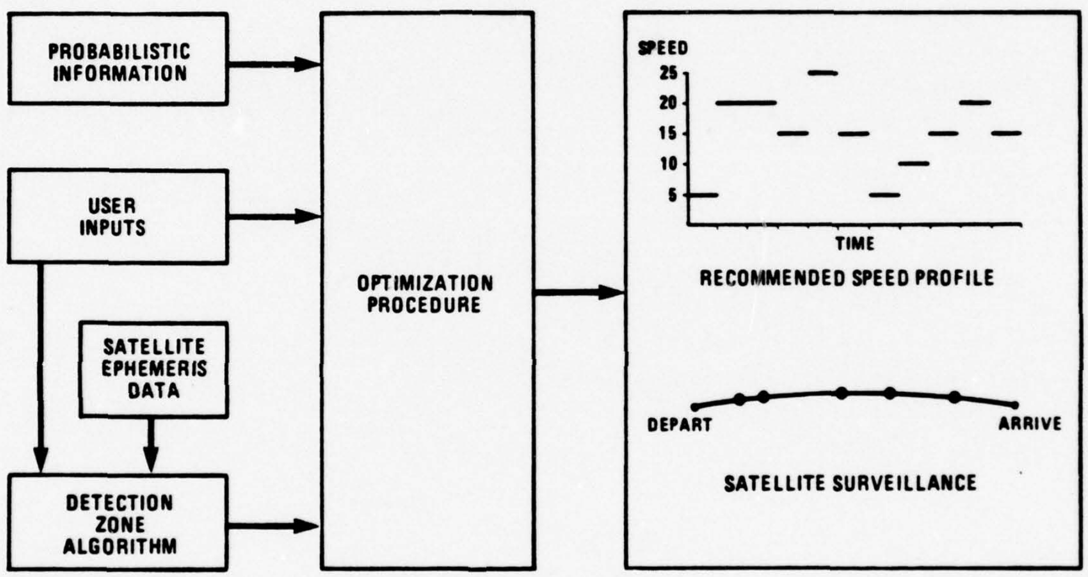


Figure 2-4
DECISION AID OVERVIEW

of advance are are obtained from the user. Then, the recommended SOA profile is computed as the one that minimizes the expected cost of the transit.

2.3.2 User inputs - Required user inputs are listed in Figure 2-5. First the user must supply the departure time and arrival time. Ordinarily these parameters are treated as though they were fixed during the optimization process; that is, the optimizer will assume departure is on time and will assure on-time arrival. However, if the user is willing to allow a zero speed of advance as a possibility, the optimizer will suggest that the task force depart late or arrive early if there is any advantage in doing so.

Next, the departure point, the intermediate points (if any) and the destination are supplied, defining the user's track plan. If no intermediate coordinates are specified, a great circle route is assumed.

Once the track plan specification has been completed, the Aid will ask the user to assess the probability of already being tracked as he leaves his point of departure. For example, it may normally be the case that adversary ships in the area of the departure point are certain to take notice of his departure. In this case there will be a higher probability that later satellite intersections will result in a detection.

The second phase of the transit plan definition sequence begins with the specification of the SOA options to be considered in the optimization process. The user is asked to do this by providing a minimum value, a maximum value, and an increment. Although the example in Figure 2-5 shows these values to be multiples of 5, this is not

- Departure and arrival times
- Track plan (point of departure, destination, and intermediate points)
- Probability of already being tracked at departure
- SOA options
  (e.g., 5, 10, 15, 20, 25 knots)
- Time increment for SOA changes
  (e.g., 8 hours)
- Fuel costs
- Detection aversion costs
- Evasive action costs

Figure 2-5

USER INPUTS

a requirement; the only restriction is that the minimum SOA and the maximum SOA must be multiples of the SOA increment. The minimum SOA may in fact be zero or negative.

Following the specification of SOA options, the Aid asks the user to select a time increment to be used in the optimization process as the length of time over which SOA's will be maintained. When a particular SOA value is chosen by the optimizer, the user is expected to maintain that speed for his task force for the duration of the time increment specified. The optimizer will consider changing speeds only at times which are multiples of this time increment.

For the example shown in Figure 2-5, the time increment of 8 hours has been chosen. Thus, the optimizer will consider SOA changes with a frequency of three times a day.

The next portion of the transit plan definition process is concerned with the assessment of "fuel costs." The user is asked to specify the relative "costs" of the various SOA options with respect to one another and with respect to other criteria considered later in the elicitation process, namely, detection aversion and evasive action costs.

The fuel costs assessed here ordinarily reflect more than just the cost of fuel associated with each SOA option. They indicate the user's aversion to using each particular SOA option relative to the others (and relative to the other two criteria) for any reason whatsoever. For example, the user may prefer an SOA of 10 knots to one of 5 knots because his ships do not respond as well to the helm in heavy seas at the slower speed.

Detection aversion, like fuel costs, must be assessed in relation to the entire set of cost criteria. Detection aversion is a measure of the cost to the user if he were detected during his planned transit (and identified as a target of interest) by hostile surveillance forces. Like fuel costs, aversion to detection could be expressed simply as a single value. It may happen, however, that a user's aversion to detection varies as a function of his progress through his transit. In particular, the user may be more concerned with detection near the end of the transit than near the beginning. To accommodate situations such as this, the user is permitted to specify a cost function over the entire course of his transit.

The final step in the transit plan definition sequence is the assessment of costs for the various evasive actions which may be employed to thwart detection.

2.3.3 Detection Zone Algorithm - The detection zone algorithm provides the requisite information for plotting the detection zones in Figure 2-3. In the current Aid, it uses hypothetical orbital parameters for five surveillance satellites. In an operational decision Aid, the ephemeris data for satellites would be supplied and updated regularly by a land-based computer network.

The output of the detection zone algorithm may be summarized in a table, as illustrated in Figure 2-6.

2.3.4 Probabilistic Information - Probabilistic information is used in the dynamic program to calculate the probability that the task force will be detected when it passes through a detection zone. This information includes, for example, the probability that the weather is OK for

Potential Detection Zones

No	Type	Date-Time	Coverage*	No	Type	Date-Time	Coverage*
1	R	17 NOV 0633	2611-2672	31	E	18 NOV 0125	1992-2532
2	R	17 NOV 0805	1758-1828	32	C	18 NOV 0129	226- 726
3	C	17 NOV 0902	3019-3511	33	E	18 NOV 0253	960-1520
4	R	17 NOV 0935	835- 924	34	E	18 NOV 0422	0- 488
5	O	17 NOV 0952	2801-3225	35	R	18 NOV 0628	2658-2718
6	I	17 NOV 0957	2798-3128	36	R	18 NOV 0800	1805-1875
7	E	17 NOV 1006	3461-3615	37	C	18 NOV 0821	3532-3615
8	C	17 NOV 1030	1765-2317	38	R	18 NOV 0930	890- 978
9	O	17 NOV 1125	1751-2003	39	C	18 NOV 0947	2360-2929
10	I	17 NOV 1131	1759-1951	40	E	18 NOV 0955	3585-3615
11	E	17 NOV 1134	2265-2960	41	O	18 NOV 1028	2387-2633
12	C	17 NOV 1158	672-1172	42	I	18 NOV 1033	2389-2575
13	R	17 NOV 1253	3480-3542	43	C	18 NOV 1116	1180-1701
14	O	17 NOV 1258	702- 979	44	E	18 NOV 1123	2446-3097
15	I	17 NOV 1304	715- 928	45	O	18 NOV 1201	1351-1610
16	E	17 NOV 1304	1027-1658	46	I	18 NOV 1207	1362-1560
17	C	17 NOV 1325	0- 133	47	C	18 NOV 1243	142- 628
18	R	17 NOV 1424	2447-2609	48	R	18 NOV 1248	3522-3585
19	E	17 NOV 1433	0- 549	49	E	18 NOV 1253	1168-1810
20	R	17 NOV 1552	901-1004	50	O	18 NOV 1334	267- 559
21	O	17 NOV 1933	2945-3190	51	I	18 NOV 1339	280- 505
22	I	17 NOV 1939	2877-3061	52	R	18 NOV 1420	2570-2736
23	O	17 NOV 2104	1526-1852	53	E	18 NOV 1423	111- 682
24	C	17 NOV 2108	3569-3615	54	R	18 NOV 1547	964-1070
25	I	17 NOV 2109	1435-1682	55	R	18 NOV 1717	0- 42
26	O	17 NOV 2236	382- 658	56	O	18 NOV 1835	3562-3615
27	C	17 NOV 2236	2318-2803	57	I	18 NOV 1841	3493-3615
28	I	17 NOV 2241	306- 514	58	O	18 NOV 2009	2386-2759
29	E	17 NOV 2356	3185-3615	59	I	18 NOV 2014	2282-2564
30	C	18 NOV 0002	1265-1745	60	O	18 NOV 2140	1056-1359

*Nautical miles from point of departure.

Figure 2-6

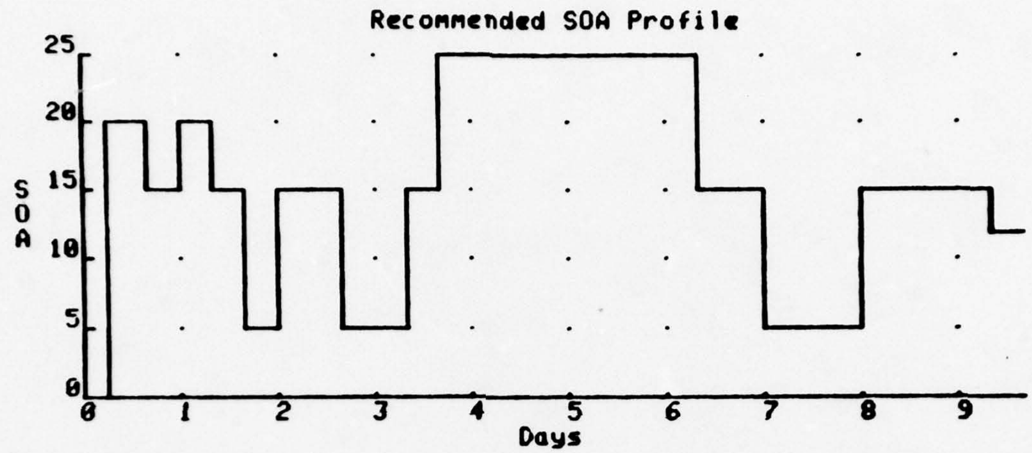
POTENTIAL DETECTION ZONES

detection, the probability that the satellite is operating if the weather is O.K., and the probability that the satellite will detect the task force if it is operating and the weather is O.K. The way in which these probabilities depend on the particular detection zone under consideration must be carefully specified.

For example, the probability that weather is O.K. for detection depends on when and where the detection zone occurs and on the satellite's sensors (optical sensors would be defeated by cloud cover whereas radar sensors would not). Also, the probability of detection given that the satellite is operating and the weather is O.K. depends on what local cover and deception tactics the commander can employ (COMINT sensors would be defeated if the commander employs EMCON).

A complete probability model for the Aid has been specified, but it requires probability assignments from weather and satellite experts. A practical way to make these assignments must be developed before the Aid becomes operational.

2.3.5 <u>Decision Aid Output</u> - The decision Aid supplies the commander with a recommended SOA profile and, for that profile, a listing of the satellite detection zones that will be encountered. Computer-graphic displays are shown in Figures 2-7 and 2-8.

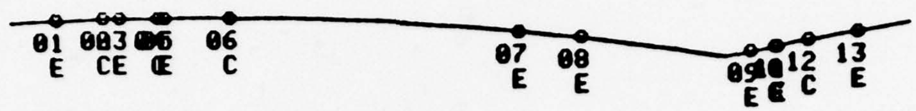


Date-Time	SOA
17 NOV 0600	20
17 NOV 1600	15
18 NOV 0000	20
18 NOV 0800	15
18 NOV 1600	5
19 NOV 0000	15
19 NOV 0800	15
19 NOV 1600	5
20 NOV 0000	5
20 NOV 0800	15
20 NOV 1600	25
21 NOV 0000	25
21 NOV 0800	25
21 NOV 1600	25
22 NOV 0000	25
22 NOV 0800	25
22 NOV 1600	25
23 NOV 0000	25
23 NOV 0800	15
23 NOV 1600	15
24 NOV 0000	5
24 NOV 0800	5
24 NOV 1600	5
25 NOV 0000	15
25 NOV 0800	15
25 NOV 1600	15
26 NOV 0000	15
26 NOV 0800	12

Figure 2-7

RECOMMENDED SOA PROFILE

Detection Zones under Recm'd SOA Profile



No	ID	Lat	Lng	Date/Time	Expos*	Action
1	E	37.3N	72.8W	17 NOV 1433	2.3	EMCON
2	C	37.6N	69.0W	18 NOV 0129	2.0	EMCON
3	E	37.6N	67.8W	18 NOV 0422	2.3	EMCON
4	C	37.8N	64.8W	18 NOV 1243	2.0	EMCON
5	E	37.8N	64.3W	18 NOV 1423	2.3	EMCON
6	C	37.8N	59.1W	19 NOV 1201	2.0	EMCON
7	E	35.0N	36.3W	22 NOV 0209	2.3	EMCON
8	E	33.8N	31.5W	22 NOV 1207	2.3	EMCON
9	E	30.9N	18.1W	24 NOV 0017	2.3	EMCON
10	C	31.8N	16.2W	24 NOV 2204	2.0	EMCON
11	E	31.9N	16.0W	25 NOV 0007	2.3	EMCON
12	C	32.9N	13.6W	25 NOV 0915	2.0	EMCON
13	E	34.5N	9.7W	25 NOV 2355	2.3	EMCON

* Minutes

Figure 2-8

DETECTION ZONES UNDER RECM'D SOA PROFILE

3.0 CONCLUSIONS AND RECOMMENDATIONS

The Satellite Surveillance Avoidance Optimization Aid described in this report provides the naval commander with a significantly improved method for surveillance avoidance. The Aid will not be ready for actual deployment, however, without additional enhancements or improvements, and one of the main purposes of using it at ACCAT is to investigate and develop needed enhancements.

3.1 Interface Enhancements

One obvious area in which the Aid requires enhancement is in its user interface. The manner in which parameters are requested and results are presented is a matter which involves subtle psychological factors and is often subject to personal taste. DDI has considerable experience in the design of man-computer interfaces and has implemented an effective interface for the Optimizing Aid. Nonetheless the Aid is certain to require at least some "fine tuning" in this area. We recommend that the user-interface enhancements incorporated into the Aid be based upon the experience gained through the use and testing of the Aid at the ACCAT.

3.1.1 Avoidance Profile and Detection Zone Displays - One example of a potential user-interface enhancement concerns the Intercept Avoidance Profile and the Detection Zones displays shown in Figures 3-1 and 3-2, respectively. Both of these displays indicate the points along a given transit where detection by a satellite is possible, that is, the points for which a commander's transiting force lies within a satellite footprint. It is important to note that merely lying within the footprint does not mean that detection by the satellite is certain or even likely. The satellite may not be in operation, the weather may be unsuitable

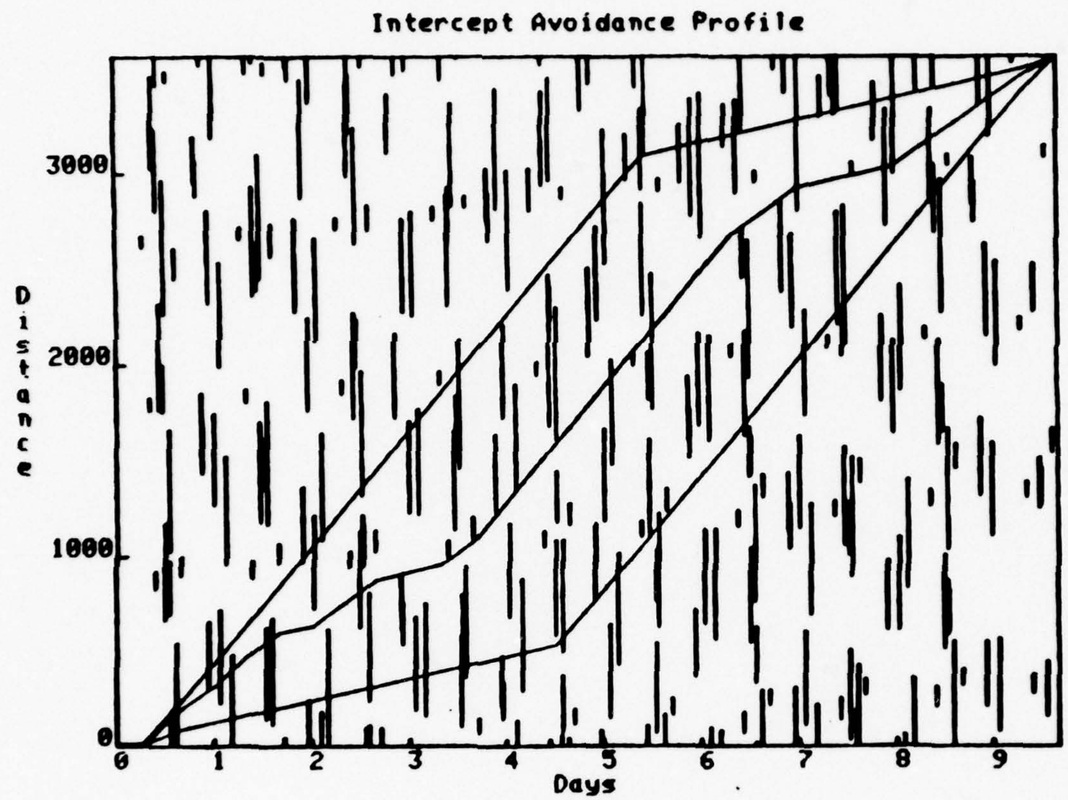


Figure 3-1

INTERCEPT AVOIDANCE PROFILE

Detection Zones under Recm'd SOA Profile

No	ID	Lat	Lng	Date/Time	Expos	Action
1	E	37.4N	72.0W	17 NOV 1433	2.3	EMCON
2	I	37.6N	68.5W	17 NOV 2241	0.8	NORMAL OPERATIONS
3	C	37.7N	67.2W	18 NOV 0129	2.0	EMCON
4	C	37.8N	59.1W	19 NOV 1201	2.0	EMCON
5	E	35.0N	36.3W	22 NOV 0209	2.3	EMCON
6	E	33.8N	31.5W	22 NOV 1207	2.3	EMCON
7	E	30.9N	18.2W	24 NOV 0017	2.3	EMCON
8	C	31.0N	17.9W	24 NOV 2204	2.0	EMCON
9	C	32.3N	15.0W	25 NOV 0915	2.0	EMCON
10	E	34.0N	11.1W	25 NOV 2355	2.3	EMCON

Figure 3-2

DETECTION ZONES UNDER RECM'D SOA PROFILE

for detection, or the evasive action employed may thwart detection. It is desirable, therefore, to know the probability of detection associated with each "intercept." (Detection probability is calculated during the optimization process for each potential detection zone. Thus, no special calculations are required to provide this information). Communicating the probability of detection to the user can be accomplished in several ways.

Two possible mechanisms for this are (1) to label each intercept with its probability, and (2) to display subsets of the intercepts which exceed user-specified probability thresholds.

3.1.2 Single scale for cost factors - Another example of a potential user-interface enhancement concerns the specification of relative costs. Extensive psychological research on the ability of human beings to process information in various judgmental tasks has indicated that humans are far better at comparative judgements than at absolute ratings. This implies that in order to avoid the effects of various cognitive limitations that lend to unreliability and inaccuracy in absolute judgmental tasks, humans should be used as null instruments to make direct comparisons of objects, e.g., "Object A is heavier (or worth more) than Object B. If Object A is worth 100, Object B is worth 70." This is one of the reasons that procedures for scaling value (or utility) using human judgments should utilize comparative judgements, involving well-established reference points.

In this vein, a procedure for establishing a single scale that encompasses the relative costs of the different factors involved in the Optimizing Aid, such as fuel cost, detection aversion, and evasive action cost might be valuable so that relative scaling procedures that involve direct comparisons of the different factors are used.

The Aid could be changed to provide the user with a summary feature which displays all the costs on a single scale, and allows the user to reset values on that single scale.

3.1.3 Non-numeric scale - Operational navy personnel may experience some difficulty in expressing their personal value systems by means of an arbitrary numeric scale such as the one described above. To overcome this problem, it may be possible to assess at least some of the costs in terms of a "harder" metric, such as dollars, hours of delay, etc. Alternatively, it may be possible to develop an assessment mechanism which employs verbal quantifiers rather than numeric values. DDI is currently conducting research in this area, attempting to exploit the current state of the "fuzzy set" methodology developed by Zadeh et al. It is still too early to tell whether usable results will evolve from this research.

3.1.4 Standard strategies - Notwithstanding the relative merits of numeric versus verbal quantifiers, the parameter set of the Aid allows the user considerable latitude and flexibility in describing his particular value system to the optimizer. The user can define with a high degree of precision how much he values avoiding detection versus employing the various evasive actions versus steaming at the various SOA options. On the other hand, having that degree of freedom means that the user must give careful consideration to the specification of his cost functions.

One can imagine situations in which the naval commander has a frequently used global objective in mind, such as "avoid detection at all costs." Rather than requiring him to formulate a set of values to implement this objective each time he wants to employ it, it would be

convenient for him to have it available as part of a set of "standard strategies" known to the Aid.

The Aid could contain a set of "canned" strategies available to all users. Since it is unlikely that one could achieve universal agreement on the values constituting any one strategy, let alone several, it seems more practical and useful to allow the user to define his own set of standard strategies. When a commander has developed a set of parameter values for an objective which he might like to employ again at a later time, he could save it in his personal collection of strategies. Over time each collection could develop to the point of containing most of the strategies employed by its owner and could save the user considerable effort in planning a transit. Moreover, with experience, the user will have tuned his strategies so that they very closely reflect his inner value system.

Because of its potential appeal, we recommend incorporation of such a standard-strategy feature into the Aid.

3.1.5 Location name - The Aid currently requires the user to indicate his planned points of departure, destination, and intermediate track points by specifying their latitudes and longitudes. Since few users have this type of information committed to memory (particularly the casual user expected for demonstrations at the ACCAT), we recommend providing the optional capability to specify such points by location name. With this feature, the user will have at his disposal a list of, say, a hundred of the most commonly used ports and operational points of departure and destinations. The user will then be able to specify a transit from Norfolk to Gibraltar simply by answering "Norfolk" and "Gibraltar" in response to the requests for point of departure and destination.

3.2 Evasive Action Options

For initial testing and demonstration of the Aid, we have defined seven evasive action possibilities for thwarting the satellite sensors (including the "non-action," Normal Operations). While this set of actions is representative of an operational environment, it is not as rich as it might be. For example, the evasive action list contains only one EMCON option, defined to be "total EMCON" in which <u>all</u> transmitters are assumed to be turned off. Other types of EMCON could be defined as follows (in order of decreasing restriction from total EMCON):

- Allow UHF communications for vital reports only.
- Allow discrete (intermittent) use of active radar search and air control systems.
- Allow use of beacon tracking and target identification systems.
- Allow use of HF radio tactical reporting systems.
- Allow full use of tactical surveillance, defense, and air control systems.
- No restrictions.

(Each of these options includes the use of all systems permitted at each higher level.)

Most of the other evasive actions in the current set could be expanded into more precisely defined options as well. We recommend incorporating the EMCON options defined above into the evasive action set. If the richer set of EMCON options results in significantly different probabilities

of detection, then soliciting other evasive action and cover and deception (C&D) options from users at ACCAT and incorporating them into the set appears worthwhile.

3.3 Sensitivity Analysis

Another feature which bears consideration is a capability for sensitivity analysis. It would be beneficial for the user to explore the consequences of varying his departure and arrival times, varying intermediate points in his track plan, varying his SOA options, or varying his cost functions. Unfortunately, variations of this sort require, at a minimum, iteratively performing the optimization calculations, and in many cases recalculating potential satellite intercepts as well. Since these are relatively costly undertakings, this sort of "brute force" sensitivity analysis appears reasonable only when there is little constraint upon the computer resources available and when there is ample time available before actual departure.

This does not preclude the development of sensitivity analysis features, however. One sort of sensitivity analysis mechanism which may be feasible is to permit the user to specify probability density functions for parameter values (rather than point values) and to generate corresponding outcome value distributions. This could result in the generation of several SOA profiles with associated expected levels of effectiveness. We recommend investigating mechanisms of this sort and implementing one which appears to provide the greatest level of feedback to the user.

3.4 SOA Constraints

In an operational environment, there are situations for which a naval force must limit its SOA options to a subset of those generally available for a given transit. For

example, at a given point in the journey, it may be necessary to conduct replenishment operations, in which case the commander might wish to restrict his SOA to 10 knots for a specific eight-hour period. As another example, in inclement weather the commander might wish to go no slower than 10 knots to maintain steerageway and yet may be unable to exceed 15 knots because of the sea conditions.

To accommodate situations such as these, we suggest providing the capability for the user to specify for selected time periods SOA constraints which restrict the number of SOA options to be considered by the optimizer to a subset of the SOA options defined for the transit.

3.5 Cost Function Segmentation

In planning a particular transit, the naval commander may choose his course in such a way that his cost functions (detection aversion, fuel cost, and evasive action costs) and the efficacies of the various evasive actions are significantly different over different segments of the journey. For instance, a portion of the route may coincide with merchant shipping lanes. In this case, the effectiveness of reconfiguration or EM spoof to simulate a merchant task force are markedly improved over the effectiveness of these actions when far removed from the shipping lanes. In another situation, the route may pass through an area which normally contains a high level of naval activity. For this area the commander's aversion to detection may be significantly lower than for the rest of the journey.

In order to provide the flexibility desired for situations such as these, we recommend incorporating into the Aid features which allow the user to specify detection aversion, fuel cost, evasive action costs, and evasive action level of effectiveness independently for each segment of a journey.

The number of segments and the extent of each should be selectable by the user.

3.6 Fuel Consumption

One aspect of transit cost upon which many of the early users of the Aid have focused is fuel consumption. Although the user is expected to define a fuel cost function for the optimizer, this cost function really encompasses more than just fuel cost and might better be considered an "SOA cost function," since it can reflect other reasons for disliking one SOA more than another (such as reduced steerageway).

In order to provide the commander with a more concrete measure of his fuel consumption, reports on percentage of fuel remaining on each of his ships at destination might be useful. The user would be expected to indicate the composition of his force by type of ship and the initial fuel load on board each. Based upon the distance to be traveled, the SOA profile recommended by the Aid, and known fuel consumption rates, the Aid could calculate the amount of fuel remaining on each ship at the end of the transit.

This feature could provide the commander with another mechanism for assessing the costs of a journey.

3.7 Principle of Optimality

The principle of optimality states (in over-simplified terms) that if one deviates from an optimal strategy, he should develop a new (optimal) strategy rather than try to reconcile himself with the old strategy, which in fact will no longer be optimal.

The implications of this for the naval commander are that if he deviates from the SOA profile recommended by the

Aid, he should not attempt to "catch up" or resynchronize with that profile. Rather, he should request a new SOA profile which is optimal for his current set of circumstances. The original SOA profile is optimal only as long as the force departs from the stated point of departure at the specified departure time <u>and</u> follows the recommended SOA profile, causing position as a function of time to vary as shown in the Intercept Avoidance Profile of Figure 3-1. If the force deviates from the recommended SOA profile, its position will not coincide with the curve of Figure 3-1, but will lie above or below it at any instant in time. While it may be possible to adjust SOA in such a way as to rejoin the "optimal" curve, doing so may cause the task force to pass unnecessarily through avoidable detection zones (the vertical lines of Figure 3-1). To maintain optimality, a new SOA profile is required.

Fortunately, very little recalculation is required to produce the new SOA profile (as long as the force has not deviated from its planned course and as long as its position still lies within the parallelogram of Figure 3-1). By saving the set of optimal SOA choices for all lattice points within the parallelogram (instead of discarding them once the original SOA profile has been produced), the Aid would have all the information required to generate an optimal SOA profile from any position within the parallelogram.

In light of the significant possibility of deviations from the recommended SOA profile in an operational environment, we feel that the reoptimization facility is worthwhile and we recommend that it be added to the Aid.

3.8 <u>Graphics Language</u>

In an effort to improve the response characteristics

of the user interface software (currently resident in a Tektronix 4051 intelligent graphics terminal) and to approach a greater level of standardization for all software installed at the ACCAT, DDI recommends converting the user interface software of the Aid to be compatible with the newly defined Graphics Language. Since the 4051 software is written in BASIC and the Graphics Language support software is currently compatible only with FORTRAN, BLISS, and MACRO, the conversion will necessarily involve a major rewrite of the user interface.

3.9 SOA Profile Evaluation

The primary objective of the Aid is to assist a naval commander in his planning by providing him with an optimal SOA profile for satellite surveillance avoidance. There may be situations for which avoidance of satellite surveillance is of secondary importance, however, and for which a fixed SOA profile already has been selected (perhaps to minimize the chance of detection by acoustic sensors).

In its larger role as a planning tool, the Aid could also function as an evaluation mechanism. Given a specific SOA profile, the Aid could at a minimum inform the user of the detection zones which the force will encounter. It could also suggest the appropriate evasive action to minimize the cost of detection for each zone. In addition, it could provide a comparison of the cost and probability of detection over the transit for the given SOA profile and the optimal SOA profile.

As a step in the evolution toward a comprehensive transit planning aid, we suggest incorporating the SOA profile evaluation features into the current Aid.

3.10 Other Enhancements

Although this list of possible enhancements is not exhaustive, we feel that it is representative of a larger set of potential enhancements, some as yet unspecified. We plan, therefore, to be alert to the possible existence of such enhancements, extensions, and modifications to the Optimizing Aid and to implement those which appear most cost beneficial.

3.11 ACCAT Installation

The Aid is currently installed at DDI on a Tektronix 4051 intelligent graphics terminal and a PDP-11/40 which acts as the host computer. In accordance with the goal of demonstrating and testing the Aid in the ACCAT environment, the Aid must be installed on ACCAT hardware, which is presumably a 4051 terminal and a PDP-10 or a DECsystem 20.

Although no major obstacles are expected, some software modifications will be required to effect the transfer. In particular, those portions of the software which deal with communications and I/O and those which contain word-length dependencies will have to be changed. Most of the modification effort will be concentrated on the host software. Only the "login" and host communication portions of the 4051 software will be affected.

3.12 Installation and User Support

In order to facilitate use and demonstration of the Aid in the ACCAT, DDI recommends providing training, consultation, and software support services for ACCAT personnel. During a twelve-month period, we expect that several trips to NOSC

of two or three days' duration would be required to accomplish this task. As part of this task, appropriate documentation on the use of the Aid in the form of a users' guide should be provided.

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Recent technological advances have made possible sophisticated data-gathering capabilities for earth-orbiting spacecraft. Naval forces would appear to be particularly vulnerable to satellite surveillance since they operate on the surface of uniform, low-noise oceans where camouflaging is difficult. over

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A methodology is presented for helping a naval commander avoid satellite surveillance. With known satellite orbital characteristics, the time and location of detection zones along a ship's planned route can be calculated. It is suggested that a commander can avoid many of these detection zones by varying his speed as a function of time. A graphical representation is presented and its limitations are discussed.

A decision aid based on this methodology has been developed. It uses probabilistic information, such as weather, to find the expected number of detections for any speed profile. An optimal speed profile is found by means of dynamic programming.